Impacts of Evaporation from Raindrops on Tropical Cyclones. Part II: Features of Rainbands and Asymmetric Structure

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ABSTRACT

In this study, the impacts of evaporative cooling from raindrops on a tropical cyclone (TC) are examined using cloud-resolving simulations under an idealized condition. Part I of this study showed that evaporative cooling greatly increases the kinetic energy of a TC and its size because rainbands provide a large amount of condensation heating outside the eyewall. Part II investigates characteristics of simulated rainbands in detail. Rainbands are actively formed, even outside the eyewall, in the experiment including evaporative cooling, whereas they are absent in the experiment without evaporative cooling. Rainbands propagate in the counterclockwise and radially outward direction, and such behaviors are closely related to cold pools. New convective cells are successively generated at the upstream end of a cold pool, which is referred to here as the upstream development. The upstream development organizes spiral-shaped rainbands along a low-level streamline that is azimuthally averaged and propagates them radially outward. Asymmetric flows from azimuthally averaged low-level wind advance cold pool fronts in the normal direction to rainbands, which are referred to here as cross-band propagation. The cross-band propagation deflects the movement of each cell away from the low-level streamlines and rotates it in the counterclockwise direction. Cross-band propagation plays an essential role in the maintenance of rainbands. Advancement of cold pool fronts lifts up the warm and moist air mass slantwise and induces heavy precipitation. Evaporative cooling from raindrops induces downdrafts and gives feedback to the enhancement of cold pools.

1. Introduction

Evaporative cooling has significant impacts on the development and structure of a tropical cyclone (TC) through changes of convective activity. In Sawada and Iwasaki (2010, hereafter Part I), it is shown that when evaporative cooling is included (control experiment) rainbands are actively formed, which produce large amounts of condensation heating at not only the eyewall but also the outside. The diabatic heating associated with rainbands greatly drives the secondary circulation of the TC and transports the absolute angular momentum inward. The enhanced angular momentum continuously increases the kinetic energy of a TC and expands the TC size (radius of gale-force wind), when compared with the experiment excluding evaporative cooling (NOEVP experiment). On the other hand, in the NOEVP experiment rainbands hardly appear outside the eyewall and it retains its size very well. Roles of rainbands are considered to be important for TC characteristics because TC size is closely related with rainband activity. Thus, herein we aim to study the formation, propagation, and maintenance mechanism of rainbands through the cloud-resolving simulations of the Japan Meteorological Agency (JMA) Nonhydrostatic Model (NHM).

Many observational studies by radar or aircraft have been done on the shape, structure, and propagation of rainbands in a TC. Wexler (1947) showed the spiral shape of rainbands from radar observation and suggested influences from the low-level streamlines on its formation. Observed radar echo patterns elongate at the upstream end of rainbands and propagate radially outward (Senn and Hiser 1959; Tatehira 1961). Senn and Hiser (1959) indicated that the internal gravity waves and cross-band shear of the upper-level winds provide the mechanism for the outward propagation of the individual echoes. Tatehira (1962) remarked that the old eyewall propagates outward from the TC center and the
new one is formed inside the old one. MacDonald (1968) described the shape of rainbands from radar scope and satellite images and its analogy of the propagation to tropospheric troughs of general circulation (Rossby waves). Willoughby et al. (1984) and Shimazu (1997) classified types of rainbands from their movement speed, where one type featured almost motionless rainbands with respect to the TC center (a stationary band complex, or slow-moving band) and the other featured cyclonically rotating rainbands (a moving band, or fast-moving band). Stationary and long-lived rainbands, which were found by photographic mapping (Malkus et al. 1961), are formed by the interaction between the TC vortex and its environmental flows (Willoughby et al. 1984; Shapiro 1983), and moving rainbands have a close relationship with internal gravity waves (Willoughby et al. 1984). In contrast, Shimazu (1997) showed that features of moving rainbands contradict internal gravity waves. These observational studies can capture parts of rainband features; however, it is not sufficient to bring out the dynamical and thermodynamic structure of rainbands yet.

Barnes et al. (1991) suggested that cold pools play an important role in the rainband maintenance, from airborne observation. Some observational studies reported the decrease of temperature with the passage of rainbands (Ushijima 1958; Tatehira 1962; Barnes et al. 1983; Powell 1990b). However, such cold pools are not always observed (Tatehira 1961; Ishihara et al. 1986; Shimazu 1997). It is very difficult to capture a three-dimensional (3D) structure of cold pools and to reveal its roles in rainbands from only observational data. Hence, 3D cloud-resolving simulations are desired to clarify the cold pool behaviors.

Theoretical and numerical studies on rainband formation and propagation are roughly classified into the following three categories: cold pools (Yamasaki 1983, 1986), internal gravity waves (Abdullah 1966; Kurihara 1976; Willoughby 1978; Chow et al. 2002), and vortex Rossby waves (VRWs; Guinn and Schubert 1993; Montgomery and Kallenbach 1997). Yamasaki (1983) showed from cloud-resolving simulations of two-dimensional axisymmetric models that cold pools are essential for rainband formation and radially outward propagation. Though axisymmetric models cannot explain the spiral-shaped structure and azimuthal propagation of rainbands, 3D simulations are desired. Yamasaki (1986, 2005) remarked that rainbands are reproduced using a 3D model with parameterized cold pool effects. However, it is not enough to resolve the detailed structure of rainbands resulting from coarse horizontal grid spacing (about 15 or 20 km).

Abdullah (1966) attempted to model observed features of rainbands as propagating internal gravity waves and to explain its features. Kurihara (1976) showed from the linearized equations for small perturbations that rainbands might be interpreted as outward-propagating internal gravity waves. Some numerical simulations showed that the rainbands seem to act as internal gravity waves (Anthes 1972; Kurihara and Tuleya 1974; Jones 1977). However, Yamasaki (1983) indicated a possibility that cumulus parameterization misleads characteristics of gravity waves in their models.

Guinn and Schubert (1993) remarked that inner rainbands are interpreted as potential vorticity wave breaking, and the merger uses f-plane shallow-water equations. Montgomery and Kallenbach (1997) examined outward-propagating spiral rainbands such as VRWs. In spite of many attempts to understand the rainbands’ formation and propagation, the impacts of evaporative cooling on rainbands behaviors using 3D cloud-resolving simulations are not fully understood yet.

Thus, the purpose of this study is to clarify what roles evaporative cooling has in rainband formation, propagation, and maintenance using 3D cloud-resolving simulations of the TC under an idealized environment. Section 2 presents shape, propagation, maintenance mechanisms, and downdraft formation of simulated rainbands from numerical experiments. In section 3, whether features of simulated rainbands are consistent with those of observed ones, and the relationship between present results and proposed mechanisms for rainband propagation in the previous numerical studies are discussed. Finally, section 4 concludes the significant results in this study.

Detailed model descriptions and the experimental design are given in the companion paper (Part I). Here, the same simulations will be analyzed focusing on the behavior of rainbands.

2. Results

2.1. Impact of evaporation on rainband formations

In Part I, the evaporation from raindrops was shown to cause considerable amounts of precipitation on the outside of the eyewall. Figure 1 shows time–radius cross sections of azimuthally averaged precipitation and tangential wind speed averaged from the surface to 5.14-km height (same as Fig. 3 in Part I). In the control experiment, precipitation areas begin to form around the TC center at $T = 24$ h and intense precipitation areas [\(>5\) mm (10 min)$^{-1}$] are seen around a radius of 20 km from the TC center at $T = 48$ h. On the outside of an eyewall, heavy precipitation areas propagate radially outward from a radius of 40 km to greater than 200 km from the TC center whose speeds are 1–4 m s$^{-1}$. Here, the radially outward propagation of azimuthally averaged precipitation is referred to as “radially outward
propagation.” As mentioned in Part I, the strong wind area gradually enlarges outward in the control experiment. On the other hand, in the NOEVP experiment the precipitation areas are observed around a radius of 40–100 km from the TC center at $T = 12–36$ h, which almost do not extend radially outward. At an intensification stage ($T = 36–48$ h), intense precipitation areas concentrate around the TC center. After $T = 48$ h, precipitation areas hardly form outside the eyewall (greater than a radius of 60 km from the TC center) and the outward propagation is not observed at all. In accordance with these features, the strong wind area does not expand after $T = 30$ h. It is evidenced from the comparison between the two experiments that evaporative cooling has significant impacts on propagation of convective activity and TC size.

Radially outward propagation of precipitation shown by Fig. 1 is mainly attributed to rainbands. Figure 2 displays the temporal change of horizontal structures of precipitation (left columns) and potential temperature at a height of 20 m (right columns) from 48 to 96 h with 12-h intervals over a domain of $300 \times 300$ km$^2$ in the control and NOEVP experiments. In the control experiment, precipitation areas are organized into the ring shape around the eyewall and the spiral shape (rainbands) on the outside. Spiral-shaped rainbands frequently emerge outside the eyewall. Rainbands are 10–30 km wide and 50–500 km long and their lifetimes are about
FIG. 2. (left) Temporal change of horizontal structure of precipitation and (right) potential temperature at a height of 20 m from 48 to 96 h, with 12-h intervals over a domain of $300 \times 300$ km$^2$ in the control and the NOEVP experiments, respectively. The interval of radii for circles is 30 km. Contour values of the precipitation are 2, 10, and 30 mm h$^{-1}$. 
12 h or less. Rainbands rotate in a counterclockwise direction around the TC center. In the NOEVP experiment, precipitation areas are almost absent on the outside of a radius of 60 km from the TC center. Band-shaped precipitation areas are formed around the eyewall; however, these do not propagate radially outward and their lifetimes are 2 h at most. By comparison with the control experiment, the evaporative cooling is considered to play an essential role in the formation of radially outward-propagating rainbands.

There appear to be significant cold anomalies, so-called cold pools, below the rainbands in the control experiment in the right column in Fig. 1. They are generated by evaporative cooling from raindrops and form axially asymmetric structures. In the control experiment, the radial distribution of potential temperature fluctuates significantly with time. In contrast, the NOEVP experiment cannot form cold pools resulting from a lack of evaporative cooling, and it has an almost symmetric structure of potential temperature. In the NOEVP experiment, the radial distribution of potential temperature hardly changes with time and decreases with radius—these features are significantly different from those in the control experiment. The basic-state potential temperature is 1–3 K greater in the NOEVP experiment than in the control experiment. Although the NOEVP experiment has a larger static instability, rainbands are absent. The results indicate that cold pools may have an important role in the formation of rainbands.

**b. Upstream development of rainbands**

Rainbands tend to lie along low-level streamlines. Figure 3 displays horizontal distributions of simulated rainbands and streamlines at a height of 260 m hourly from 65 to 70 h over a domain of $300 \times 300$ km$^2$ in the control experiment. The same streamlines are drawn in all the panels, following averaged wind azimuthally and temporally for $T = 65–70$ h, so streamlines at each of the panels are the same. Low-level streamlines blow toward the TC center from the outer side, where the angle to a concentric circle (crossing angle) is $10^\circ–20^\circ$. Individual convective cells are roughly arranged in a spiral shape along streamlines and the crossing angle of some rainbands is smaller than that of streamlines. It is noteworthy that rainbands deflect on the right-hand side (outer side) from low-level streamlines, although those do not propagate along the streamlines. The propagation mechanism for rainbands will be discussed next in section 2c.

The spiral shape of rainbands is caused by the successive development of convective cells at the upstream end of the rainband, which is referred to here as “upstream development.” For the upstream development, it is found that cold pools are a key factor to interact with inflows within the planetary boundary layer (PBL). To investigate the process of the upstream development, detailed horizontal structures of a rainband are shown in Fig. 4. Shaded regions show vertically accumulated rainfall (rainbands) and contours show precipitation (left column), azimuthally averaged potential temperature anomaly (middle column), and horizontal convergence (right column). Solid, thick lines with arrows are streamlines drawn from azimuthally averaged wind at a height of 260 m temporally averaged from 64 h to 64 h 40 min. Labels A–D indicate individual convective cells. Cold pools appear markedly below the convective cells in the middle column. They are formed by evaporative cooling from raindrops as will be discussed in section 2d. Cold pools produce horizontal convergences at the near surface between the upstream side of cold pools and low-level inflows along streamlines, and its lifting forms new convective cells B–D. New convective cells are successively generated at the upstream end of a convective cell A, which are organized into the spiral-shaped rainband along the low-level, azimuthally averaged streamlines propagating radially outward. Thus, cold pools play an essential role in the upstream development.

**c. Cross-band propagation of rainbands**

As shown in Figs. 3 and 4, moving rainbands significantly deflect from the low-level streamlines and almost follow along concentric circles, although the spiral shape of rainbands is roughly arranged along the streamlines. This deflection means that the moving direction is different from the azimuthally averaged wind. As will be shown later (Fig. 6), anomalous winds near cold pools, which steer convective cells, are almost normal to the band. Thus, the movement of rainbands is referred to as “cross-band propagation.”

To examine movement of individual convective cells, Fig. 5 illustrates the positions and shapes of the rainband from 63 h 50 min to 64 h 40 min with 10-min intervals. Here, only focusing convective cells are plotted. Dashed lines are concentric circles where the distance from the TC center is indicated. Solid lines with arrows are azimuthally averaged streamlines at 260-m height, which are roughly arranged along a spiral rainband. A convective cell seen at $T = 63$ h 50 min moves along the concentric circle and hardly propagates radially. At the upstream side of the cell, a new convective cell is generated by upstream development and also moves in the counterclockwise direction not in the radial direction. The counterclockwise motion of cells consists of a vectorial sum of azimuthally averaged flows and cross-band motion, which deflects movement of cells away from the streamlines. Hence, each cell tends to move along the concentric circle by propagating cross-band direction,
FIG. 3. Horizontal distributions of simulated rainbands and low-level streamlines hourly from 65 to 70 h over a domain of 300 × 300 km² in the control experiment. Shaded areas display vertically accumulated rainwater. Thick solid lines with arrows are the azimuthally and temporally averaged streamline for T = 65–70 h at a height of 260 m.
FIG. 4. The rainband formation from 64 h to 64 h 40 min over a domain of 120 × 120 km² in the control experiment. Contours depict horizontal distribution of vertically accumulated rainwater with contour values of 2, 10, and 30 kg m⁻². Shaded areas display (left) precipitation, (middle) potential temperature anomaly from an azimuthally averaged temperature at 20-m height, and (right) horizontal convergence. Thick solid lines with arrows are streamlines azimuthally and temporally averaged at a height of 260 m.
and the rainband seems to propagate radially outward, combined mainly with upstream development.

Cross-band propagation of rainbands has a close relationship with cold pools accompanied with cold downdrafts. Figure 6 displays horizontal structures of the cold pool at 64 h 30 min. It must be noted that a wind anomaly is normal to the rainband near the cold pool front. Within the cold pool, evaporative cooling associated with a strong precipitation forms the cold downdraft, and the downdraft and the diabatic cooling enhance cold pool within the PBL. The downdraft provides dry air from the midtroposphere to the PBL (Fig. 7c), which has an effect of keeping the evaporation of rainwater within the PBL. Momentum transport and horizontal divergence resulting from the downdraft advance the cold pool front in the normal direction to the rainband (cross-band propagation). Cross-band propagation of cold pools produces lifting for the next convective cells at their fronts, giving a positive feedback to the maintenance of rainbands.

d. Maintenance mechanism of rainbands

Some rainbands are maintained for about 10 h or more despite a short lifetime of individual convective cells (about 1 h or less). The cross-band propagation plays a significant role in the maintenance mechanism for rainbands and prevents rainbands from being entrained into the eyewall. Figure 7 shows vertical structures of the rainband along line A1–A2 shown in Fig. 6b. Progression of the cold pool forces high equivalent potential temperature air to lift up, and it easily reaches the condensation level of lower than 1-km height (Figs. 7a,b). The condensation heating accelerates the updraft, whose axis slants inward with height, to its vertical velocity of more than 8 m s\(^{-1}\) around 4.5-km height. On the inner side of the updraft, cloud water is converted into rainwater and its peak is seen at around 3-km height. Its evaporative cooling produces the cold downdraft, and the downdraft and the diabatic cooling enhance cold pool within the PBL. The downdraft provides dry air from the midtroposphere into the PBL. Momentum transport and horizontal divergence resulting from the downdraft advance the cold pool front in the normal direction to the rainband (cross-band propagation). Cross-band propagation of cold pools produces lifting for the next convective cells at their fronts, giving a positive feedback to the maintenance of rainbands.

e. Effects of water loading on downdraft

It is important to clarify contributing factors of downdrafts, because downdrafts have a large impact on rainband behavior through divergent flows and downward momentum transport. As shown in Fig. 7a, downdrafts are generated below the melting layer so that ice-phase processes do not affect the formation of downdrafts, which is consistent with Sawada and Iwasaki (2007). It remains possible that not only evaporative cooling, but also water loading, contribute to the downdraft formation. Thus, a sensitivity experiment to water loading (NOWL), which excludes an effect of water loading of rainwater, is performed.

The occurrence of downdrafts is not significantly different among the control, NOEVP, and NOWL experiments at 4.22-km height in Fig. 8a. At 1.14-km height, the occurrence of downdrafts has little difference between the control and NOWL experiments in Fig. 8b; however, the occurrence of strong downdrafts (\(<-3\) m s\(^{-1}\)) is about one digit less in the NOEVP experiment than in the control experiment. Therefore, water loading has no significant impact on the downdraft formation and evaporative cooling is a major factor for it. It is noteworthy that in the NOWL experiment radially outward-propagating rainbands are reproduced.

Occurrence of strong updrafts (\(>2\) m s\(^{-1}\)) at both 1.14- and 4.22-km height is quite less in the NOEVP experiment than in the control and NOWL experiments.
because in the NOEVP experiment rainbands are absent. At 1.14-km height, occurrence of strong updrafts (>5 m s\(^{-1}\)) is somewhat greater in the NOWL experiment than in the control experiment. This is considered due to the lack of a suppressing effect resulting from water loading.

3. Discussion

a. Comparison with observed rainbands

Simulated rainbands under an idealized environment are organized into a spiral shape along low-level streamlines and propagate radially outward through upstream development. Rainbands also rotate in the counterclockwise direction around the TC center through cross-band propagation, which is a key factor for the maintenance of rainbands. Here, whether features of simulated rainbands are consistent with those of observational results in the previous studies is discussed.

The spiral shape of rainbands by upstream development is consistent with the spiral shape of radar echo patterns associated with an observed TC (Tatehira 1961). The evidence of propagation of observed radar echo patterns by his study, which propagates radially outward and rotates in the counterclockwise direction, also closely resembles features of simulated rainbands.
Moving the direction of each convective cell in simulated rainbands is supported by the findings of Powell (1990a), which showed that cells move along almost a concentric circle at a speed of about 85% of the 0.2–6-km density-weighted mean wind. The counterclockwise motion of simulated rainbands is similar to moving bands categorized by Willoughby et al. (1984) and Shimazu (1997). It is found that cold pools are essential for the organization of simulated rainbands. Barnes et al. (1991) remarked that cold pools play an important role in maintaining rainbands from airborne observation, which is consistent with the results of numerical experiments. A decrease of temperature is observed during rainband passing from surface weather elements (Ushijima 1958; Tatehira 1962), and especially airborne observations (Barnes et al. 1983; Powell 1990b). However, the decrease of surface temperature with the passage of rainbands is hardly observed in some cases (Tatehira 1961; Ishihara et al. 1986; Shimazu 1997). Ishihara et al. (1986) indicated that this might be because of the lack of a dry layer at the middle and lower layer. To clarify the detailed structure of cold pools, an observation of a near-surface thermodynamic field is required.

b. Comparison with previous studies on rainband formation and propagation

In this study, evaporative cooling–induced cold pools play essential roles in the formation and propagation of rainbands. The importance of a cold pool for the rainbands’ behavior is highlighted by Yamasaki (1983), using a two-dimensional axisymmetric model; however, there are differences between his study and this study. Yamasaki’s...
4. Conclusions

Cloud-resolving simulations of a tropical cyclone (TC) are performed to investigate the impacts of evaporative cooling on the formation, propagation, and maintenance of rainbands under an idealized environment. Evaporative cooling produces radially outward propagation of precipitation, which expands the TC size through enhanced secondary circulation associated with condensation heating of precipitation outside the eyewall. Radially outward-propagating precipitation is attributed to the behaviors of rainbands, while they are hardly observed in the experiment without evaporative cooling. At very least, the features of rainbands in this study seem to be more closely related to cold pool dynamics than the proposed mechanisms for rainband formation and propagation by previous studies (internal gravity waves and vortex Rossby waves). Cold pools lead to upstream development of rainbands, which is defined as an extension of the rainband at its upstream end and cross-band propagation, which is defined as a movement of rainband normal to its rainband. Rainband behaviors result from upstream development and cross-band propagation, which are quite similar to those of the observed radar echo patterns (Tatehira 1961).

Upstream development originates from horizontal convergence between the upstream of a cold pool and low-level inflows with high equivalent potential temperature (EPT). The lifting successively generates new convective cells at the upstream end of a cold pool and organizes spiral-shaped rainbands along azimuthally averaged streamlines from the surface to the top of the PBL and propagates them radially outward. Cross-band propagation is caused by asymmetric flows from azimuthally averaged wind at the PBL. Asymmetric flows are driven by a positive pressure anomaly resulting from downdrafts and become normal to the rainband at the cold pool front (outer side). The cross-band propagation deflects movement of each cell away from the low-level streamlines. Actual movement is the vectorial sum of azimuthally averaged flows and axially asymmetric flows, and it rotates counterclockwise almost along concentric circles. Also, cross-band propagation is essential for the maintenance of rainbands. The advancing cold pool fronts lift up the high EPT air mass slantwise and make condensation. As a result of evaporation from raindrops, heavy precipitation induces downdrafts and gives a feedback to the enhancement of cold pools. The structures of simulated rainbands are consistent with those observed (Barnes et al. 1991). In addition, downdrafts are mainly produced by evaporative cooling but have less contribution by water loading.

As mentioned in Part I, the enhanced secondary circulation by condensation heating of rainbands increases kinetic energy of the TC and enlarge its size. Namely, radially outward-propagating rainbands with counterclockwise motion resulting from cold pools have significant impacts on TC size. Cold pool dynamics may be important for TC-track forecasts as well as intensity forecasts. The track forecast is sensitive to its size through its interaction with environmental flows (Iwasaki et al.)
FIG. 9. Propagation of internal gravity waves from 66 h 40 min to 67 h with 10-min intervals over a domain of $600 \times 600$ km$^2$ in the (left) control and (right) NOEVP experiments. Shaded areas show positive pressure anomaly from azimuthally averaged pressure and thin dashed contours are negative at 1.82-km height. Thick contours depict vertically accumulated rainwater with a value of 1 kg m$^{-2}$. 
1987). Toward an accurate TC forecast, it is desired to operate a high-resolution model with appropriate cloud microphysics.

This is an idealized experiment with an initial axisymmetric vortex under a horizontally uniform environment. In nature, including wind shear, baroclinicity, and beta effect, some observational studies demonstrate not only propagating rainbands but also stationary rainbands, which stay around a fixed location with respect to the TC center (Willoughby et al. 1984; Shimazu 1997). Hence, investigations of the impacts of cloud microphysics on stationary rainbands and of relationships between propagating and stationary rainbands are of great interest. Further understanding of rainbands is explored from cloud-resolving simulations of rainbands under a realistic condition.

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